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An experimental study of emission and combustion characteristics of marine diesel engine with fuel pump malfunctions

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HIGHLIGHTS

- Chosen malfunctions of the fuel injection pump of marine engine are simulated.
- Changes of thermodynamic parameters of marine engine are analyzed.
- Changes of CO, CO_2 and NOx emission characteristics of marine engine are analyzed.
- Injection pump malfunctions take significant changes in emission characteristics.

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ABSTRACT

Presented paper shows the results of the laboratory study on the relation between the chosen malfunctions of a fuel pump and the exhaust gas composition of the marine engine. The object of research is a laboratory four-stroke diesel engine, operated at a constant speed. During the research over 50 parameters were measured with technical condition of the engine recognized as "working properly" and with simulated fuel pump malfunctions. Considered malfunctions are: fuel injection timing delay and two sets of fuel leakages in the fuel pump of one engine cylinder. The results of laboratory research confirm that fuel injection timing delay and fuel leakage in the fuel pump cause relatively small changes in thermodynamic parameters of the engine. Changes of absolute values are so small they may be omitted by marine engines operators. The measuring of the exhaust gas composition shows markedly affection with simulated malfunctions of the fuel pump. Engine operation with delayed fuel injection timing in one cylinder indicates CO_2 emission increase and NOx emission decreases. CO emission increases only at high the engine loads. Fuel leakage in the fuel pump causes changes in CO emission, the increase of CO_2 emission and the decrease of NOx emission.

1. Introduction

In classic technical solution of a ship engine room a few diesel engines are installed. One or more diesel engines are installed as a main propulsion. Usually there are low speed, two-stroke diesel engines operated with fixed pitch propeller [1], or medium speed, 4-stroke diesel engines, operated at constant speed (with variable pitch propeller). Moreover, there are 2 or more power generators and one emergency power generator on the ship engine room. The power generator usually contains medium speed, 4-stroke diesel engine, operating at a constant speed. Other design solutions are encountered, e.g. based on a gas or steam turbine or electric motor with power generators. However, they are rarely used because of the lower energy efficiency of this type of systems. The marine internal combustion engines are the turbocharged diesel engines with direct fuel injections to cylinders, fueled with marine diesel oil or heavy fuel oil. A fuel delivery system of such engine consists of mechanically controlled Bosh type fuel pump and injectors with multi-hole nozzle type [2]. The first Common Rail system in marine, medium speed 4-stroke diesel engine was installed in 2001. It should be noted that in the year 2011 more than 50% of the fleet in the world had been older than 15 years (over 42.5 thousands ships above 100 gross tonnage) [3].

Operation of a marine engine causes its condition changes and decreases its efficiency. The effect of this is toxic compounds emission changes. It should be noted that the average main propulsion marine engine (nominal power equal 10 MW) emits over 3 tons of nitric oxides (NOx) per 24 h to the atmosphere, even if they meet the emission standards. A change of the technical condition, arising from the wear of engine components, causes general

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Nomenclature:

NOx	nitric oxides
CO	carbon oxide
CO_2	carbon dioxide
SFC	specific fuel consumption [g/kWh]
EGR	exhaust gas recirculation
MIP	mean in-cylinder pressure
λ	air/fuel excess ratio

deterioration of fuel spray condition [4], fuel vaporization and fuel combustion in engine cylinders. The effect of these phenomena is the increase of fuel consumption and thus the increase of carbon oxide (CO) and carbon dioxide (CO_2) emissions. The increase of fuel consumption (carbon content in fuel equals 0.35 in a molar [2]) by 1% (1.9 g/kWh) causes the increase of CO_2 emission from mentioned 10 MW power output engine by 7 tons per 24 h. Note, that presented fuel consumption change is difficult to detect in practice. The reason for this is the methodology of fuel consumption measuring on board. The standard method of fuel consumption measure is periodically checking the amount of fuel in ship tanks. It should be noted that fuel is stored on board in several tanks with overall volume often excess 100 m^3 and the fuel volume in the fuel tanks depends of all on board engines fuel consumption and temperature in fuel tanks.

Relatively small changes in the efficiency of marine engines are not being detected by the ship automation systems also. Mentioned systems of mechanical and thermodynamic parameters of the engine are set to alarm only at the extreme values. Extreme parameter values usually appear during the engine load close to the nominal or minimum. Engine generators on board usually work at partial loads. The reason for this is safety. Otherwise, a temporary increase of the demand for electric power on the ship could cause the engine overload. Presented set of automatic systems on the ship is justified by the efficiency of the ship operation. Automatic systems alert the ship's crew only in case of a significant change in mechanical and thermodynamic parameters of the engine. Only such changes should oblige to carry out repairs. Each repair increases general cost of ship operation. The effect of this approach is the situation where marine engines are being operated for a long period of time with reduced performance, resulting in a significant increase of toxic compounds emission. Therefore, it is necessary to know the impact on damage of various functional systems of marine engine not only to the mechanical and thermodynamic parameters, but the emission of toxic compounds also. Unfortunately, there are relatively few data on this subject in the literature.

Deteriorations in the combustion process cause significant changes not only in thermodynamic parameters of the engine but also in emission characteristics also. According to results, presented in Ref. [5] process of preparing the combustion mixture in the cylinder is critical for the level of toxic emissions and engine efficiency. The indirect injection causes decrease of the NOx and CO fractions in exhaust gas but decrease of the engine efficiency. Generally the delay of the injection timing causes decrease of the combustion temperature and NOx mole fractions in the engine cylinder [6] and NOx emission in exhaust gas [7]. The result of this is increase of the CO fractions. Asad et al. [8] proposed fuel injection timing control algorithm to heat release optimization for small diesel engine with common rail and EGR systems. This trend is visible in different engine constructions; in the low heat release engines [9] with pistons coated with ceramic materials and heavy duty engine with common rail system [10]. According to results, presented in Ref. [11] the NOx emissions decrease for very early injection (38° before top dead center of the crankshaft position). The reason of these phenomena could be the decrease of heat release rate [7]. It should be noted that delaying of the injection fuel increases soot emission [12,13]. Commonly used strategy is the fuel multiple injection. This strategy was studied in Refs. [14,15]. According to presented results the early pilot fuel dose injection causes decrease of NOx, CO and soot emission in exhaust gas and heat release rate also. In 2004 Lindgren et al. [16] showed the emission characteristics of toxic compounds from two diesel engines (low nominal power compared to power of marine engines) operated in transient conditions. The results showed that transients in engine speed and torque in most cases increase the fuel consumption and emission amounts.

The NOx emission characteristic of the engine depends on humidity of air. The experimental investigations results of diesel combustion with water emulsion [17] show that the 20% addition of the water steam to the air inlet duct decreases the NOx and CO_2 fractions in exhaust gas but increases the CO fraction in overall the engine speed condition. Similar results are reported in Refs. [18,19] for 10% and 15% of the steam water addition.

The influence of the fuel properties on the engine emission characteristics was extensively studied. According to [20] increasing diesel fuel cetane number gives earlier ignition with less time for pre-ignition mixing and lower level of the NOx emission.

Only Ref. [20] of the presented relation to the medium speed diesel engines which parameters are close to parameters of marine engines. It should be noted, that a lot of works about combustion and emission from the diesel engines can be find in the scientific literature. Mentioned works concerns, however, small engines used in on road and off-road vehicles. Marine engines have a different design and a different the combustion process organization.

The most important differences are: a low speed, a lengthened stroke, a shortened angle of fuel injection, and an extended the combustion process into the expansion stroke. These differences mean that the conclusions from the experimental studies on small engines are not applicable for large marine engines.

Lack of new research activities concerning the impact of the marine diesel engine malfunctions on emissions forced the author to undertake the research work. The main goal of the manuscript is finding qualitative dependences between the selected malfunctions of marine diesel engine fuel pump and change of both thermodynamic parameters and toxic emissions. Mentioned dependences may be useful to looking for the signals to recognize the malfunctions of the engine during on board operation.

This paper presents the results of laboratory tests on the effects of selected fuel pump malfunctions on the level of emissions.

2. Laboratory setup and procedure

The study were carried out using a marine, 3-cylinder, four-stroke, direct injection diesel engine type AL25/30 Cegielski–Sulzer manufacturer with an intercooler system, installed in Laboratory of Internal Combustion Engines in Gdynia Maritime University. The engine was loaded with a generator electrically

Table 1
Diesel fuel oil properties.

Parameter	Value	Unit
Density at 15 °C	827.3	kg/m^3
Kinematic viscosity at 40 °C	2.636	mm^2/s
Cetane number	53.2	–
Sulfur content	3.8	mg/kg

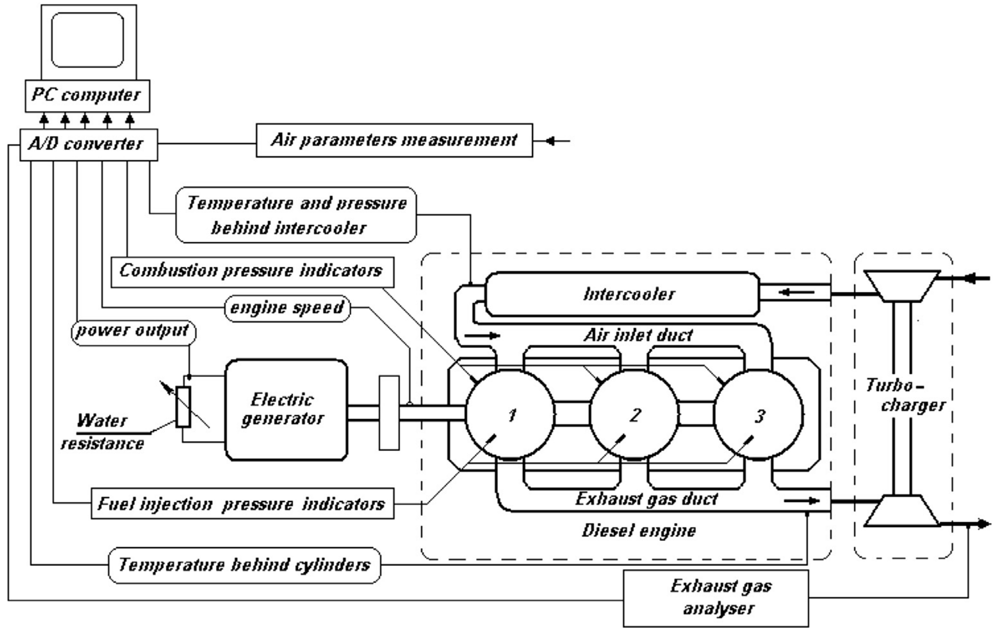

Fig. 1. The laboratory stand scheme.

connected to the water resistance and supercharged by VTR 160 Brown-Boveri turbocharger. During tests the engine was fueled by diesel oil with properties presented in Table 1 and operated at constant speed, equal to 750 rpm. The fueling system of the engine consists of mechanically controlled Bosh type fuel pumps connected to injectors with multi-hole type nozzles. This type of engine is commonly used as a power generator or main propulsion system with variable pitch propeller. 56 parameters of the laboratory stand, including the engine load and speed, parameters of the turbocharger, systems of cooling, fueling, lubricating and the air exchange were measured. The composition of exhaust gas was also recorded using electrochemical gas analyzer with infrared carbon dioxide sensor. Pressure, temperature and humidity of the air were also recorded by laboratory equipment. All mentioned results were recorded with 1 s sampling time. Injection and combustion pressure in all cylinders of the engine were also recorded. The scheme of the laboratory stand is presented in Fig. 1. The most important engine parameters are presented in Table 2 and the precisions and ranges of measurement equipment are presented in Table 3.

The experimental study consists of 4 stages of 3 observations with simulations of different malfunctions of the fuel pump installed in second cylinder of the engine. During each start of the observation, the engine was loaded to maximum load equal to 250 kW, measured as an electric power on generator, and, after stabilizing temperature of exhaust gas behind the turbine, engine operating parameters were recorded for 3–5 min. After that, the load of the engine was decreased by 10 kW and, after stabilizing temperature of exhaust gas behind the turbine, engine operating parameters were recorded again.

Observation was continued with loads up to 50 kW at a constant speed. No measurements were made at 190 kW the engine load due to resonance vibrations, manifesting in the increased engine vibration of measuring devices and high inaccuracies of rotational speed measurement. The stages of the experiment were set as follows:

- First stage during the operation of the engine assumed as “working properly”,
- Second stage during the operation of the engine with delayed fuel injection by 4.5° of crankshaft angle,
- Third stage during the operation of the engine with small leakage in the fuel pump,
- Fourth stage during the operation of the engine with large leakage in the fuel pump.

The wear on the piston and cylinder surfaces in the fuel pump cause fuel leakage to the feedback channel. Fuel pump leakage was simulated by unsealing feedback fuel channel using a screw. Leakage settings during the first observation were made on the basis of an analysis of the combustion pressure characteristic in second cylinder (see Fig. 2a). Settings were not changed during the two remaining observations. Unfortunately, method of leakage simulation presented in Fig. 2b does not allow quantifying the volume of the leakage.

Table 2
Parameters of the test engine.

Parameter	Value	Unit
Max. electric power	250	kW
Rotational speed	750	rpm
Cylinder number	3	–
Cylinder diameter	250	mm
Stroke	300	mm
Compression ratio	12.7	–
Nominal start of injection	−18°	CA
Injector nozzle		
Holes number	9	–
Holes diameter	0.325	mm
Opening pressure	25	MPa

3. Results and discussion

Laboratory research results of the engine operation recognized as “working properly” are presented in Fig. 3. According to presented results, the increase of the engine load causes the increase of the exhaust gas temperature behind engine cylinders (Fig. 3a). Exhaust gas with greater temperature delivers more energy to the turbocharger, thereby it increases charging air pressure with stable

temperature (Fig. 3b). It should be noted that marine diesel engines with mechanically controlled injection timing are usually designed in such a way that their efficiency is the highest while operating with almost nominal loads. That occurs in this case also. For this reason, the increase of load causes the decrease of specific fuel consumption (Fig. 3a). In the Fig. 3c the emission characteristics of marine engine are presented. Emission characteristics are obtained by laboratory measurements and calculations according to ISO 8178 regulations [21]. According to presented results the increase of the engine load causes the decrease of a NOx, carbon oxide (CO) and carbon dioxide (CO_2) emission levels. It should be noted that increase of the engine load causes increase of fractions of the mentioned gaseous compounds, but parallel the relative amount of the exhaust gas decreases. Moreover, presented emissions are expressed in relation to the increased the engine load.

In order to facilitate the analysis of the results, Figs. 4–7 show the mean for all observation changes of operating parameters of the engine in relation to operating parameters of engine considered as “working properly”. Mentioned changes are presented in percentage.

3.1. Fuel injection timing delay

Detrition of a surface or displacement of a cam on a camshaft may cause fuel injection timing delay. The effect of that is shifting combustion process towards the expansion stroke. During the laboratory study fuel injection timing was delayed by 4.5° in second cylinder. The result of this simulation showed the decrease of the maximum combustion pressure (Fig. 4a) and the increase of the maximum fuel injection pressure (Fig. 4b) in relations to “working properly” engine in all considered engine loads. According to the results presented in Fig. 4c, fuel injection timing delay causes the increase of mean in-cylinder pressure (MIP) in defected cylinder at low engine loads operation. It should be noted that in mechanically controlled engines the beginning of the fuel injection is set constant for all engine loads. The value of mentioned parameter is set for the best engine efficiency at nominal load of the engine. It means that decrease of the engine load deteriorates its efficiency. For this reason, the delay of fuel injection results in improved combustion conditions at low engine loads operation. The result of this is a slight decrease of specific fuel consumption (Fig. 5a), but only for engine loads up to 70 kW. Fuel injection timing delay causes the increase of exhaust gas temperature from the defected cylinder (Fig. 5b). Mentioned increase is clearly visible during low loads engine operation. As a result it provides more energy to the turbocharger (Fig. 5c), which delivers a larger amount of air to the engine. The effect of the fuel injection timing delay on the

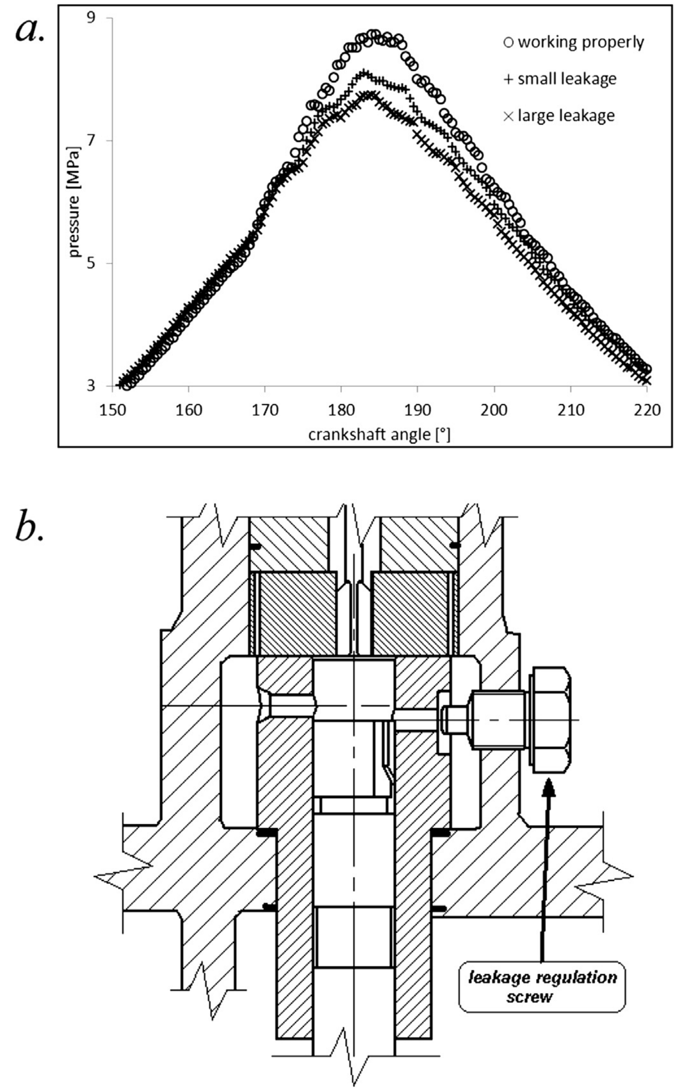

Fig. 2. Method of the fuel pump leakage simulation and identification of the fuel leakage by combustion pressure in the cylinder for 250 kW the engine load.

temperature and pressure of the charging air measured behind the air intercooler is presented in Fig. 5d and e. This malfunction causes the increase of both pressure and temperature of charged air. These changes reach 25% compared to the operation of the “working properly” engine. The changes of the turbocharger operation influenced the operation of all engine cylinders.

For this reason, the fuel injection timing delay in one cylinder also implies a slight increase of the exhaust gas temperature from other cylinders (Fig. 5f). The result of this is the increase of fuel consumption during the engine operation with loads between 70 and 200 kW.

Fuel injection timing delay causes the decrease of CO emission during low loads of the engine (Fig. 6a). The CO formation in the engine cylinders is the result of incomplete combustion. The increase of the engine efficiency during operation with low engine loads causes the decrease of CO emission. According to the mentioned considerations, fuel injection timing delay on the second cylinder causes the increase of the turbocharger performance. This increase of performance is caused by the increase of exhaust gas flow (Fig. 6b). Fig. 6c presents the air–fuel excess ratio changes with engine load changes.

Table 3
Precision values and ranges of the measurement equipment.

Parameter	Range	Precision values
Environment air temperature	0–60 °C	±0.5 °C
Environment air humidity	0–90%	±2.0%
Exhaust gas temperature	0–650 °C	±1.35%
Carbon oxide CO	0–10,000 ppm	±5.0%
Sulfur dioxide SO_2	0–5000 ppm	±5.0%
Nitric oxide NO	0–3000 ppm	±5.0%
Nitric dioxide NO_2	0–500 ppm	±5.0%
Carbon dioxide CO_2	0–50%	±0.5%
Oxygen O_2	0–25%	0.8%
Temperatures	0–100 °C	±0.35%
Pressures	0–4 bar	±0.3%
Fuel injection pressure	0–2000 bar	±1.0%
Combustion pressure	0–200 bar	±0.5%
Fuel consumption [kg/h]	–	±2.8%
Electric power [kW]	–	±0.5%

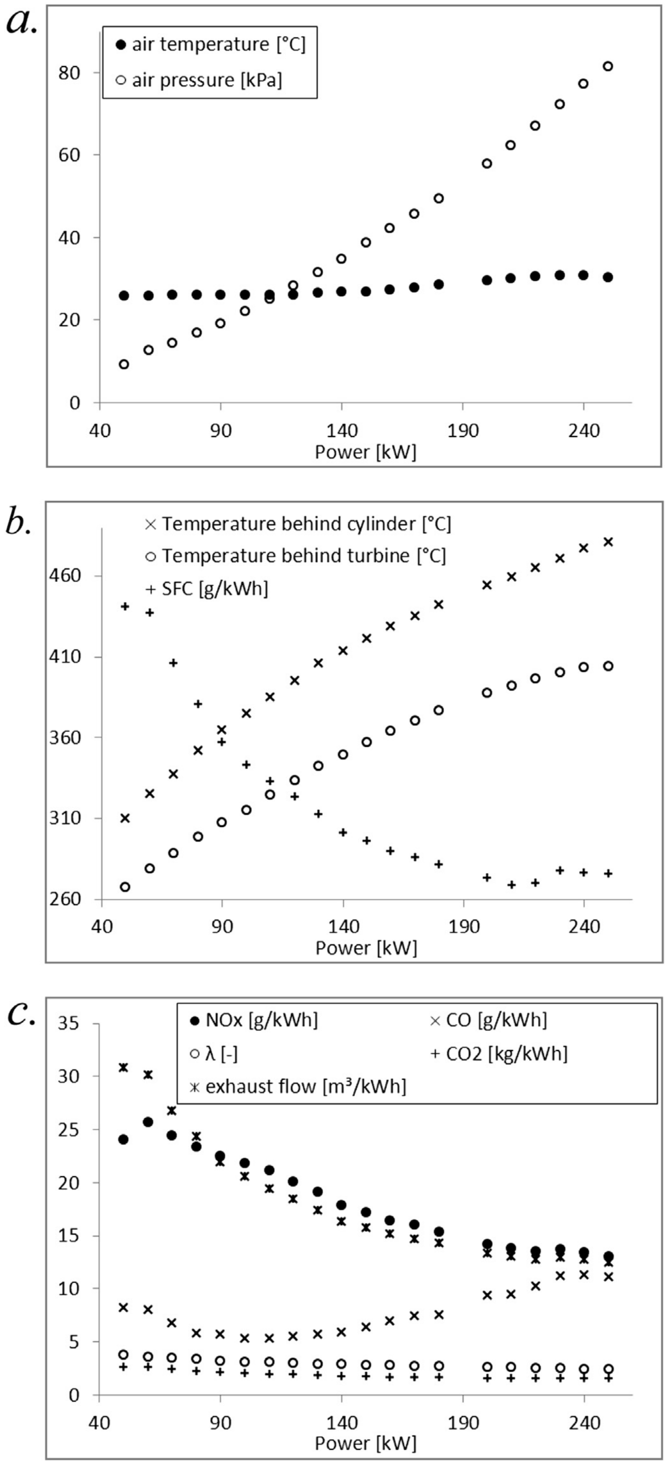

Fig. 3. Parameters of the engine assumed as "working properly".

The air–fuel excess ratio, understood as the ratio of the amount of air delivered to the engine to the quantity of air required for the fuel dose stoichiometric combustion, increases during fuel injection timing delay. Presented air–fuel excess ratio is calculated according to formula from Ref. [22]. Increased quantity of air in engine cylinders and shifting combustion process towards the expansion stroke causes probable decrease of mean combustion temperature. This conclusion was built on NOx emissions, but it was not directly proven during presented research. According to the results presented in Fig. 6d, fuel injection timing delay causes the decrease of NOx emission in all considered loads of the engine. This result was expected and qualitatively similar to results presented in Refs. [12,13,23]. The NOx emission decrease and increase of the exhaust gas temperature indicate that the combustion process is shifted towards the expansion stroke and occur at lower temperature in relation to "working properly" engine operation. This malfunction causes even 9% increase of the specific fuel consumption during the engine operation at high loads (Fig. 5a). The result is a simultaneous increase of CO_2 emission even by 12%.

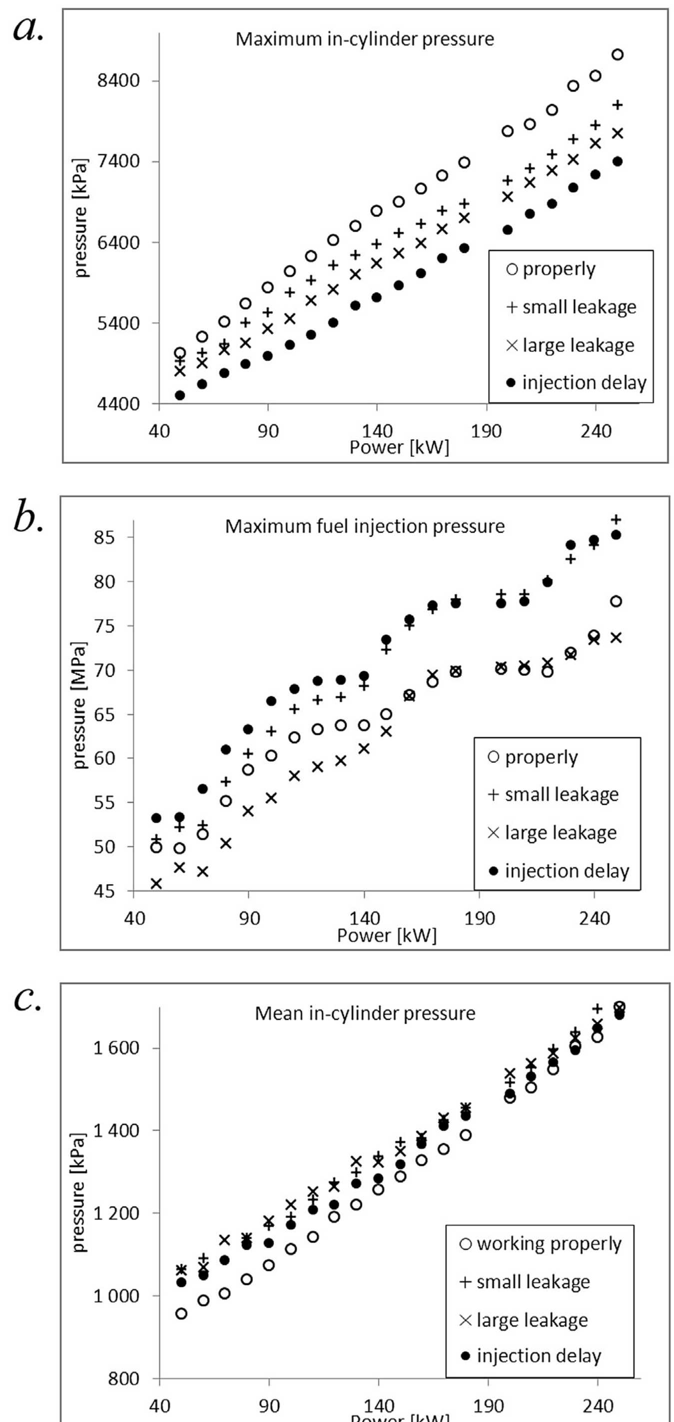

Fig. 4. Combustion in cylinder pressure and the fuel injection pressure.

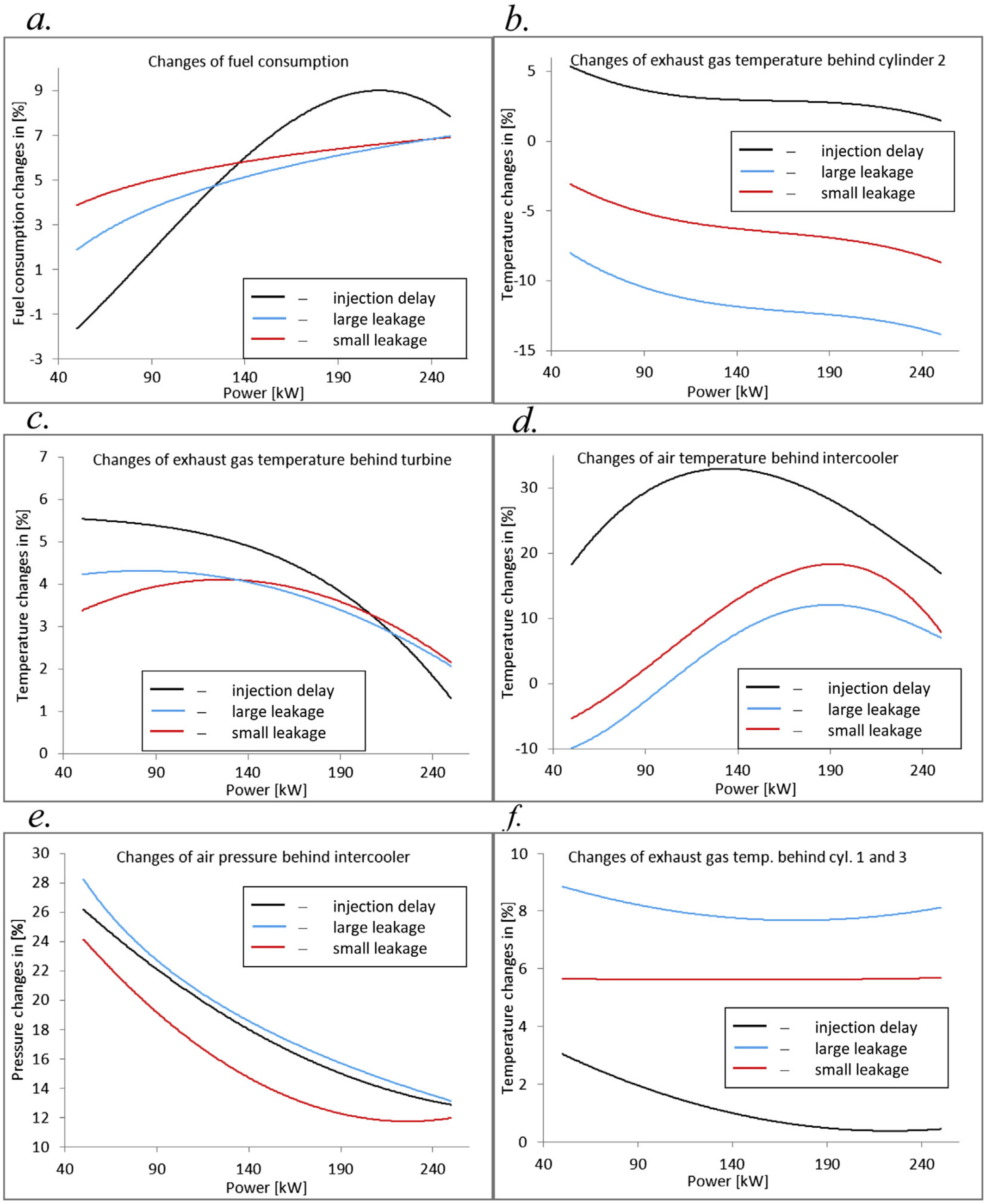

Fig. 5. Thermodynamic parameters of the engine.

3.2. Fuel leakage in the fuel pump

Detrition of elements of Bosh type fuel pump may cause fuel leakage to the feedback channel during the act of fuel pumping. The reason for this is the wear on the piston and cylinder surfaces in the fuel pump. The consequence of this fact is the injector opening delay. This delay deteriorates the general conditions of the combustion process and decreases the maximum combustion pressure in the cylinder. Fig. 4a and c presents the influence of the fuel leakage in the fuel pump on both MIP and maximum combustion pressure. The increase of the fuel leakage causes a slight increase of MIP and the decrease of a maximum combustion pressure. These changes cause deterioration of combustion process quality and the engine efficiency. Moreover, the leakage of the pump causes supplying the lower fuel dose into the cylinder. This results in the lean mixture combustion. Consequently a cylinder exhaust temperature decreases and probably overall temperature of combustion decreases also. Fig. 5f and b presents percentage changes of the exhaust gas temperature behind defected and "working properly" cylinders. According to this, the increase of the fuel leakage causes the increase of the mentioned temperature changes. Unlike the fuel injection timing delay, fuel leakage in the fuel pump causes the decrease of the exhaust gas temperature behind the defected cylinder and the increase of the exhaust gas temperature behind other cylinders. Despite the fact that the exhaust gas temperature increases to 9–13%, they are opposite to each other. Operation of the engine governor responds to the loss of power from the damaged cylinder by increasing the fuel delivery into all cylinders. As a result

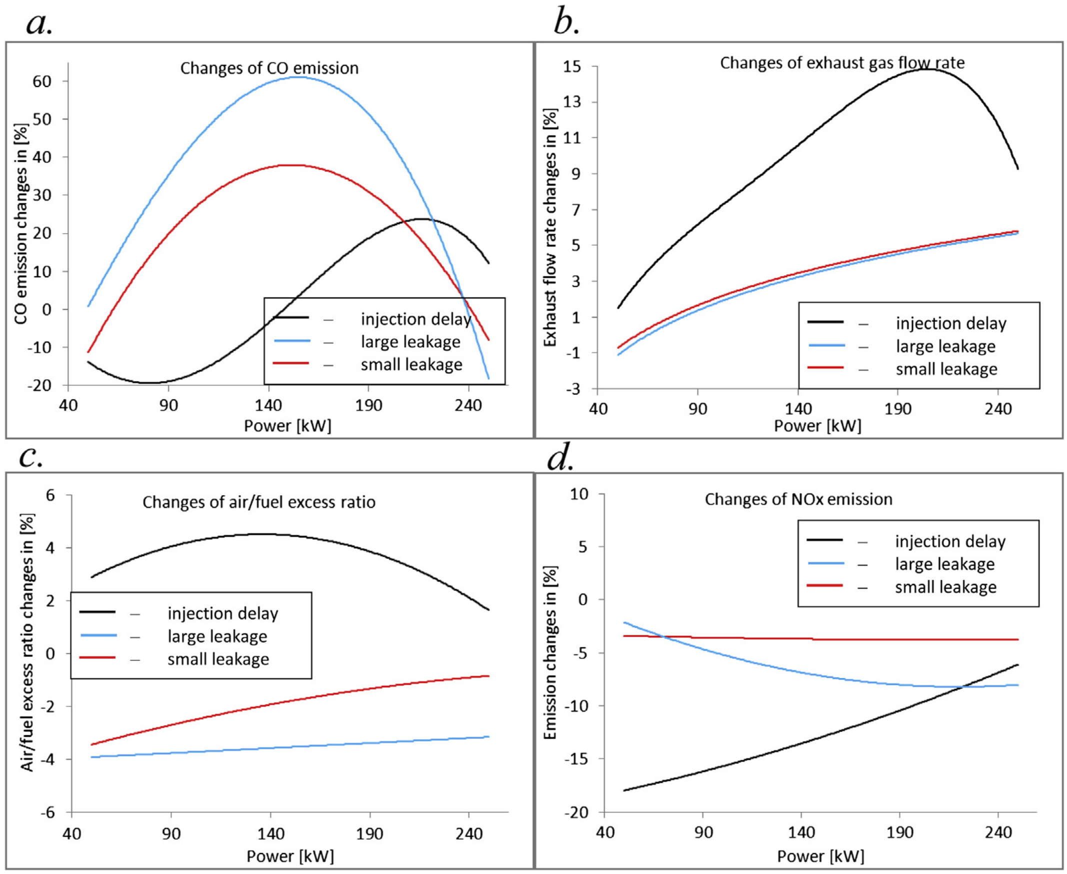

Fig. 6. Emission characteristics of the engine.

of this change the exhaust temperature behind cylinders 1 and 3 increases. It gives the effect of the even increase of the injection pressure in the damaged cylinder. The increase of the fuel pump leakage causes the decrease of injection pressure. Values of the maximum fuel injection pressures are presented in Fig. 4b. According to data presented in Fig. 5a, fuel leakage in the fuel pump causes the increase of the fuel consumption. As a result of this, the exhaust temperature behind the turbine is higher, but only by a few percent. Changes in the value of the exhaust gas temperature behind the turbine as a function of engine load are presented at Fig. 5c. The increase of the presented temperature may indicate the increase of the energy delivered to the turbine. According to the results presented in Fig. 5d and e, the change of the turbocharger operational parameters causes a considerable increase of the charging air pressure behind intercooler. The temperature of mentioned air increases also but only during engine operation with load above 90–100 kW. It should be noted that the increase of fuel leakage in the fuel pump is accompanied both by the increase of the pressure and the decrease of the temperature of the charging air behind the intercooler. These results, in correlation with the increase of the fuel consumption, indicate that the increase of the turbocharger efficiency is proportionally smaller than the increase of the fuel consumption. As a result of this, according to values presented in Fig. 6c, air–fuel excess ratio is smaller in relation to engine assumed as "working properly" for all considered loads of the engine. Consequently, the increase of both fuel consumption and the amount of charging air results in the increase of the amount of the exhaust gas emitted to the atmosphere (Fig. 6b).

Quality deterioration of combustion, as a result of the fuel leakage in the fuel pump, causes fuel consumption increase. The consequence of this is the increase of CO_2 emission. The deterioration of combustion conditions also provides a very large increase of CO emission, which, with a large fuel leakage, reached up to 60%. The dependence between both CO and CO_2 emission and the engine load are presented in Figs. 6a and 7. The decrease of the combustion temperature causes NOx emission decrease [24] in all considered loads of the engine. According to presented in Fig. 6d results, the increase of load and quantity of fuel leakage causes NOx emission decrease.

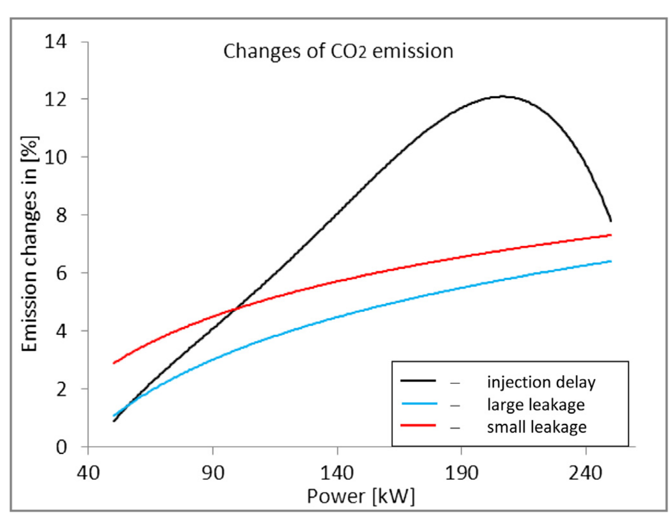

Fig. 7. CO_2 emission changes.

4. Conclusions

This paper presents the results of laboratory study on medium speed, 4-stroke, marine engine, operated with selected malfunctions of the fuel pump. As a result of the work, the following conclusions can be formulated:

1. Fuel injection delay in one cylinder of marine engine with mechanically controlled fuel injection improves its efficiency during operation with low loads. It is visible in the decrease of both fuel consumption and CO emission. The reason of these phenomena is setting the value of the beginning of the fuel injection for the best engine efficiency at nominal load of the engine. It should be noted that marine engines rarely operate at such low loads.
2. During operating with loads similar to nominal power a slight increase of exhaust gas temperature behind all cylinders and behind the turbocharger. Measurement of combustion pressure in cylinders also shows only a slight decrease of the maximum combustion pressure. The result of this is the increase of the turbocharger efficiency compared to the engine assumed as "working properly".
3. The result of increase of the turbocharger efficiency is the increase of the pressure and the temperature of the charging air behind the intercooler. Measurement of toxic compound in exhaust gas indicates CO_2 emission increase and NOx emission decrease throughout the considered loads of the engine. CO emission increases also, but only during engine operation with high loads.
4. Fuel leakage in the fuel pump, in opposition to the fuel injection timing delay, causes the decrease of the exhaust gas temperature behind the defected cylinder. The rest of the engine thermodynamic parameters experience qualitatively similar changes.
5. Measurement of the emission indicates changes in CO emission, especially at partial load engine operation. The fuel leakage in the fuel pump also causes the increase of the CO_2 emission and the decrease of oxygen mole fraction in exhaust gas in all considered loads of the engine. The decrease of the NOx emission occurs similar to fuel injection timing delay.
6. Considered fuel pump malfunctions cause relatively small changes in the thermodynamic parameters of the engine. Despite the, often large, changes in the relative values, the changes of absolute values are so small that they may be omitted by marine engine operators and the ship monitoring system.
7. According to obtained results the levels of mentioned gaseous compounds emissions may contain significant signals to recognize the mentioned malfunctions of the engine fuel pump.

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